

# The Role of Dwarf Galaxies in Building Large Stellar Halos

## A White Paper Submitted to the Decadal Survey Committee

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### Science Frontier Panels:

*PRIMARY: The Galactic Neighborhood (GAN)*

*SECONDARY: Stars and Stellar Evolution (SSE)*

### Projects Emphasized:

1. Thirty Meter Telescope, <http://www.tmt.org>
2. Giant Magellan Telescope, <http://www.gmto.org>

**ABSTRACT.** The hierarchical theory of galaxy formation rests on the idea that smaller galactic structures merge to form the galaxies that we see today. The past decade has provided remarkable observational support for this scenario, driven in part by advances in spectroscopic instrumentation. Multi-object spectroscopy enabled the discovery of kinematically cold substructures around the Milky Way and M31 that are likely the debris of disrupting satellites. Improvements in high-resolution spectroscopy have produced key evidence that the abundance patterns of the Milky Way halo and its dwarf satellites can be explained by Galactic chemical evolution models based on hierarchical assembly.

These breakthroughs have depended almost entirely on observations of nearby stars in the Milky Way and luminous red giant stars in M31 and Local Group dwarf satellites. In the next decade, extremely large telescopes will allow observations far down the luminosity function in the known dwarf galaxies, and they will enable observations of individual stars far out in the Galactic halo. The chemical abundance census now available for the Milky Way will become possible for our nearest neighbor, M31. Velocity dispersion measurements now available in M31 will become possible for systems beyond the Local Group such as Sculptor and M81 Group galaxies. Detailed studies of a greater number of individual stars in a greater number of spiral galaxies and their satellites will test hierarchical assembly in new ways because dynamical and chemical evolution models predict different outcomes for halos of different masses in different environments.

## 1 Introduction

It is well established that hierarchical merging plays a key role in galaxy formation. Observational evidence ranges from dramatic major mergers, such as the Antennae Galaxies, to subtler, low surface brightness shells around galaxies like NGC 3923. Evidence also includes long tidal streams, such as the Sagittarius stream in the Milky Way (Ibata et al. 1994), the Giant Southern Stream in M31 (Ibata et al. 2001), and large loops around NGC 5907 and other galaxies (Martínez-Delgado et al. 2008). Bell et al. (2008) found that the Milky Way (MW) halo exhibits a large amount of substructure, and very recently, the degree of kinematic substructure on the smallest scales has been quantified in a systematic, statistical search of the inner MW halo (Schlaufman et al., in preparation).

Searle & Zinn (1978) posited that the MW formed from the accretion and dissolution of dwarf galaxies. The dwarf spheroidal (dSph) galaxies that exist today may be the lone survivors from the cannibalistic construction of the Galactic halo. However, chemical abundance measurements in the last decade suggest that the stellar halo is not chemically similar to many of its dSph satellites. We address in Section 2 how these dissimilarities affect the paradigm of hierarchical assembly, which leads to a discussion of modeling the chemical enrichment of dwarf galaxies in Section 3. In the last decade, groups in several countries around the globe have focused much effort on spectroscopy of stars in the MW, but studies in the coming decade will begin to probe more distant galaxies. The structure of M31 and its satellites differs from the MW in a number of ways (addressed in Section 4), which indicates that the MW may not be representative of most galaxies. In order to make robust comparisons to theoretical predictions, a sample larger than one is necessary. In Section 5, we list some challenges for the next decade’s scientists.

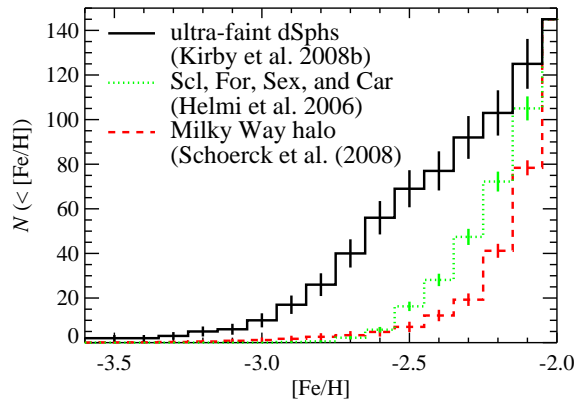


FIGURE 1: Observed cumulative metallicity distributions for dSphs and the MW halo, normalized to match at  $[\text{Fe}/\text{H}] = -2$ . The red line represents the halo measurements from the Hamburg/ESO Survey. The green line shows measurements for fairly luminous MW satellites. The black line shows  $[\text{Fe}/\text{H}]$  for eight of the faintest MW dSphs. The halo seems to have metal-poor counterparts in dSphs at all metallicities, but the shape of the dwarf galaxy MDFs is significantly weighted toward low  $[\text{Fe}/\text{H}]$  compared to the halo.

## 2 Comparing Observations of Stellar Abundances in Dwarf Galaxies to the Milky Way Halo

**In the past decade, we learned that stars in dwarf galaxies have compositions different from field stars in the MW halo.** Helmi et al. (2006) measured the metallicity distribution functions (MDFs) of some of the more luminous dSphs. The metal-poor tails of the MDFs of the most luminous dSphs (e.g., Fornax) appear similar to that of the MW halo (Schoerck et al. 2008). However, the MDFs of less luminous dSphs are more metal-poor. In fact, Kirby et al. (2008b) found much more metal-poor MDFs in Simon & Geha’s (2007) spectroscopic sample of eight of the least luminous MW satellites, including a significant population of extremely metal-poor (EMP,  $[\text{Fe}/\text{H}] < -3$ ) stars. Figure 1 summarizes the results from these three studies.

The discrepancies between the halo and dSphs also extend to elements other than Fe. The abundances of  $\alpha$  elements, such as O, Mg, Si, Ca, and Ti, together with Fe can determine the duration of star formation in a stellar system. In the beginning of the past decade, high resolution spectroscopy of individual stars in dSphs showed that the ratio  $[\alpha/\text{Fe}]$  in dSphs is lower at a given  $[\text{Fe}/\text{H}]$  than in the halo (Shetrone et al. 2001, 2003; Geisler et al. 2005, see Fig. 2).

**In the next decade, we will discover new patterns in known and soon-to-be-discovered dwarf galaxies.** The ultra-faint dwarf galaxies appear to harbor relatively large populations of the lowest metallicity stars. Detailed chemical abundances in these systems (Frebel et al. 2009) provide observational constraints on early star formation and the possibility that dwarf galaxies are the building blocks of the MW. This work is challenging because the targets are very faint for high-resolution spectroscopy ( $V \gtrsim 17$ ). Current 8–10 m telescopes can obtain spectra with adequate signal-to-noise to measure detailed chemical

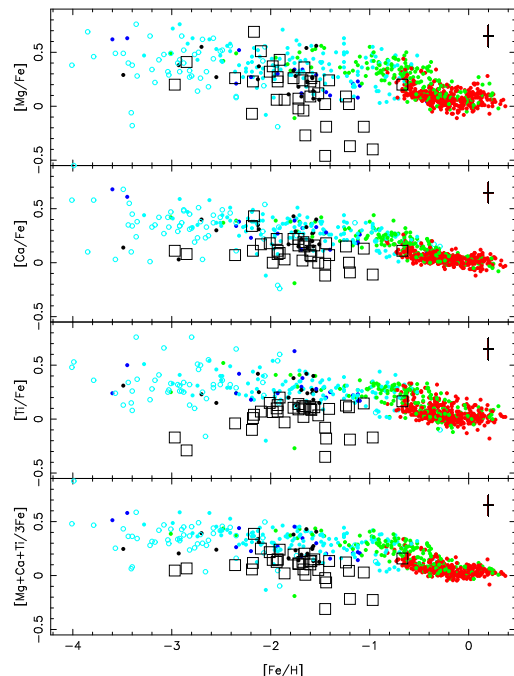


FIGURE 2: Compilation of abundances (Venn et al. 2004) in dSphs (*black squares*) and different MW components: thin disk (*red*), thick disk (*green*), halo (*cyan*), high velocity (*black*), and retrograde (*blue*).  $[\alpha/\text{Fe}]$  is lower at a given  $[\text{Fe}/\text{H}]$  in dwarf galaxies than in the halo.

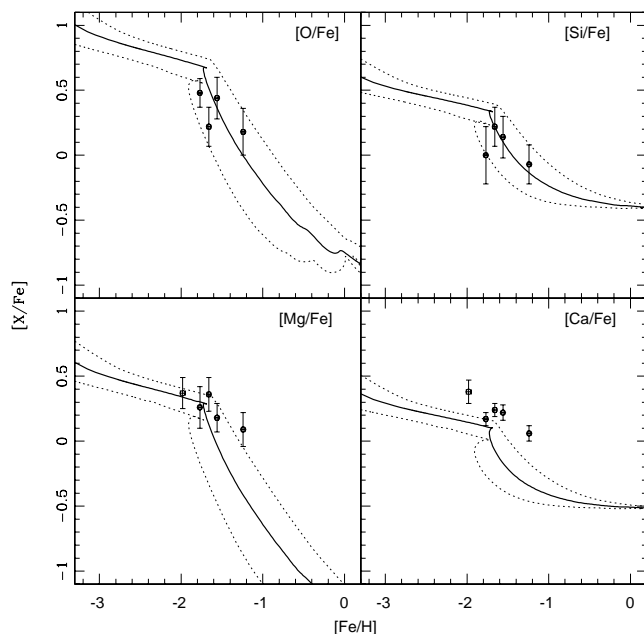


FIGURE 3: The predictions of  $\alpha$  element abundance ratios vs.  $[\text{Fe}/\text{H}]$  for the Sculptor dSph (Lanfranchi & Matteucci 2004). O and Mg are produced primarily in Type II supernovae whereas Si and Mg are produced in both Type Ia and II supernovae. As gradual star formation proceeds in a stellar system,  $[\text{Fe}/\text{H}]$  increases and  $[\alpha/\text{Fe}]$  decreases.

abundances of the brightest stars in these galaxies. Existing surveys like **SEGUE** (Yanny et al. 2009) and future photometric surveys like **LSST** (Tyson 2002), **SkyMapper** (Murphy et al. 2008), and **Pan-STARRS** (Kaiser et al. 2002) will discover more tiny galaxies. Reaching more stars and systems farther away will require a new generation of large aperture, ground-based telescopes such as **TMT** and/or **GMT**.

Multi-dimensional abundance measurements (using the technique of, e.g., Kirby et al. 2008a) for large samples of stars have very recently become available via medium-resolution spectroscopy on the largest telescopes (27 stars in the Leo II dSph, Shetrone et al. 2009, and  $\sim 400$  stars in the Sculptor dSph, Kirby et al. 2009). In the next few years, this technique, based on spectral synthesis, will permit  $[\alpha/\text{Fe}]$  and  $[\text{Fe}/\text{H}]$  to be measured simultaneously for 100–1000 red giants in many of the brighter MW dSphs. However, in the most distant dSphs (e.g., Leo I and Leo T), spectroscopy with current 8–10 m telescopes is practical for individual stars only on the upper part of the red giant branch (RGB). Further down the RGB or in more distant stellar systems, the medium-resolution spectra with 8–10 m telescopes must be coadded to attain the requisite signal-to-noise.

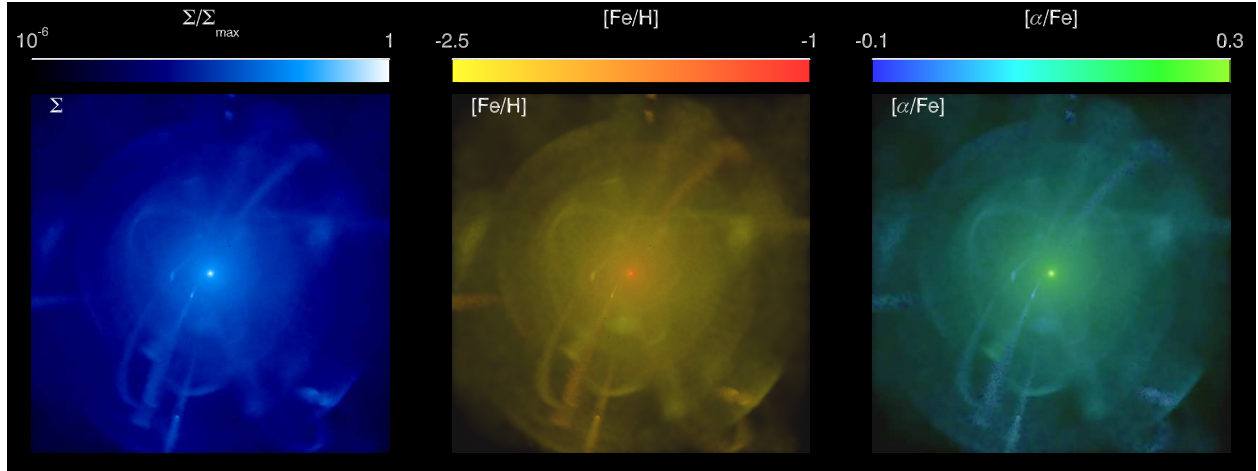


FIGURE 4: Simulation (Font et al. 2006a) of a Milky Way-sized system showing (left to right) surface brightness, metallicity, and  $[\alpha/\text{Fe}]$ . The box is 200 kpc on a side. In this model, the early, rapid construction of the diffuse stellar halo from relatively massive dwarf galaxy progenitors imprints higher  $[\text{Fe}/\text{H}]$  and  $[\alpha/\text{Fe}]$  abundances than in the cold substructure.

### 3 Modeling Chemical Enrichment in Dwarf Galaxies

**In the last ten years, we learned that chemical discrepancies between dwarf galaxy stars and halo field stars are natural consequences of  $\Lambda$ CDM cosmology.** At first glance, these discrepancies seem to challenge the assertion that the stellar halo formed mostly or entirely from dwarf galaxies. In fact, all of these discrepancies can be explained by cosmologically motivated models of star formation and chemical enrichment.

The observed chemical abundance patterns in dSphs can be explained by self-contained star formation models (Lanfranchi & Matteucci 2004; Marcolini et al. 2006, 2008). As star formation proceeds,  $[\text{Fe}/\text{H}]$  increases, but after  $\sim 1$  Gyr, Type Ia supernovae begin to lower  $[\alpha/\text{Fe}]$ . Therefore, the “knee” in the  $[\alpha/\text{Fe}]$ – $[\text{Fe}/\text{H}]$  diagram indicates the metallicity reached by about 1 Gyr, which in turn indicates the vigor of star formation. Figure 3 shows Lanfranchi & Matteucci’s (2004) model of the Sculptor dSph.

In these models, galactic winds regulate the rate of star formation. Less massive dSphs are more susceptible to losing gas to winds and therefore have slower, less efficient star formation. Because rapid star formation increases  $[\text{Fe}/\text{H}]$  quickly and keeps  $[\alpha/\text{Fe}]$  elevated, smaller dSphs tend to have lower mean  $[\text{Fe}/\text{H}]$  than larger dSphs, and an  $[\alpha/\text{Fe}]$  that begins to decline at lower metallicity. Therefore, Fig. 2 immediately indicates that the dSphs that built the majority of the MW halo were more massive than the surviving dSphs.

As Robertson et al. (2005) pointed out, this observation is completely consistent with cosmologically motivated models of galaxy formation (e.g., Bullock & Johnston 2005). In dark matter simulations, a few relatively massive satellites built the bulk of the halo  $\sim 10$  Gyr ago. Surviving dSphs continue to add stars to the halo via tidal disruption, but those dSphs are not representative of a typical halo star. Figure 4 shows the zero-redshift view of one of these MW-sized simulations with a prescription for star formation. In the context of a hierarchical formation scenario for the MW stellar halo and substructure, the surviving cold components of the halo, including dSphs and debris streams, may exhibit lower  $[\text{Fe}/\text{H}]$  and

lower  $[\alpha/\text{Fe}]$  than the inner stellar halo owing to their low masses and extended star formation histories. The inner halo may have been constructed from more massive, rapidly-forming systems that have comparably enhanced  $[\text{Fe}/\text{H}]$  and  $[\alpha/\text{Fe}]$  abundances.

**In the coming decade, synergy between model predictions and observations will advance our understanding of the origin of the MW halo.** It is difficult to directly observe the progenitors of the bulk of the halo because they have already been destroyed. However, it is possible to connect the properties of surviving dSphs and stellar halos using models of galactic star formation and chemical enrichment. These simulations make predictions about the kinematics (Helmi et al. 1999; Font et al. 2006b) and chemistry (Font et al. 2006a) of the relics of accretion events. Confirmation of these predictions will require coordinated spectroscopic surveys focused on measuring radial velocities and multi-dimensional abundances for a large number of stars. One such survey targeting the Galactic bulge is **APOGEE** (Allende Prieto et al. 2008).

The number of stellar chemical abundance measurements in dwarf galaxies and the MW halo is steadily increasing, and extremely large, ground-based telescopes will reach further down the luminosity function, rapidly multiplying that number. The quality of chemical evolution models will evolve with the quality of the data. In particular, we require a working model of star formation in the tiniest galaxies. Recent evidence for a threshold galaxy mass for star formation (Strigari et al. 2008) begs for a theoretical explanation that could also account for the abundance patterns in tiny dwarf galaxies. Can the same model also explain the abundances of EMP halo field stars, supporting the hypothesis that they originated in tiny dwarf galaxies? These observations will be complemented by star formation studies from space-based photometry (e.g., **JWST**).

As more data becomes available, abundance patterns may be scrutinized in finer detail. Forthcoming high-resolution spectroscopy will increase the body of data on neutron-capture elements in dwarf galaxies and the halo. Given the discrepancies in  $\alpha$  elements between the dwarf galaxies and the halo, it would not be surprising to find that the abundances of heavier elements also diverge. A chemical evolution model of those elements will be required to explain these observations. Can the same chemical evolution model describe the heavy element patterns in both dwarf galaxies and the halo? Or will the heavy element abundances teach us that at least some halo stars could not have been born in dwarf galaxies?

## 4 Galaxies and Environments Are Not All the Same

**Recent observations of M31 have taught us that the MW system is not representative of all spiral galaxies.** At first sight, the MW and M31 are both examples of typical late-type galaxies, but closer inspection elucidates subtle but important differences. For example, M31 seems to have had a more violent merger history than the MW (Ibata et al. 2001; Guhathakurta et al. 2005). Furthermore, the demographics of the satellite populations are different. M31, unlike the MW, possesses no known dwarf irregular galaxies. The MW, unlike M31, possesses no dwarf elliptical galaxies. Even the surviving M31 dSphs have different structural parameters than their MW counterparts (McConnachie & Irwin 2006; Peñarrubia et al. 2008).

Another powerful prediction of the simulations discussed in Section 3 is the difference



between the MW and galaxies of different sizes. Font et al. (2008) and Gilbert et al. (2009) test the metallicity predictions of these simulations on observations of M31, and the same models could make predictions about how  $[\alpha/\text{Fe}]$  in the M31 system differs from the MW system. M33 and NGC 55 offer even more dramatic comparisons. (NGC 55 has the advantage of being face-on for easier disk-spheroid separation.) Although both are star-forming, spiral galaxies, their masses are much smaller than and have different gas content from the MW or M31. Cosmological simulations would predict measurably distinct kinematic and abundance patterns for the halos and dwarf galaxies of M33 and NGC 55 compared to the MW or M31. Contrasting predictions can be made even between M33 and NGC 55 based on their broader environments. M33 lies close to M31 whereas NGC 55 is a likely companion of NGC 300, a much smaller galaxy than M31—and also a good candidate for future medium-resolution spectroscopy. The many galaxies in the Sculptor and M81 Groups would provide even more data for this comparison if they were observable. These groups exhibit different galaxy mass distributions, velocity dispersions, and intra-group gas densities, all of which can yield different, testable predictions in numerical simulations of galaxy assembly.

**In the next decade, we will test in detail hierarchical assembly models in galaxies beyond the MW.** Many predictions for M31 and the Sculptor and M81 Groups are not testable with present observational capabilities. Kinematic measurements of individual stars are limited to the MW and M31, and abundance measurements of individual stars are limited to the MW and its satellites. Extremely large telescopes of the next decade may greatly increase the distance (and hence the variety of galaxies) to which these measurements are possible. Spectra of individual stars in M31 with resolving power of  $R \sim 6000$  and signal-to-noise of  $\sim 30 \text{ \AA}^{-1}$  are feasible with the next generation of optical telescopes. With longer exposures, even the tip of the RGB in NGC 55 would be reachable with a spectral quality capable of yielding multi-dimensional abundances. With spectral coaddition of individual stars, galaxies in the Sculptor and M81 Groups would become accessible. These spectroscopic observations will rely on wide-field photometric surveys, such as **LSST**, **Pan-STARRS**, and **SkyMapper**, which will accurately characterize the level of substructure and discover new satellites around galaxies other than the MW. Ground-based spectroscopy will also complement observations from space-based telescopes, such as **JWST**, which will measure the star formation histories of distinct components of galaxies more distant than the MW and M31 (see the white paper by T. Brown et al., “The History of Star Formation in Galaxies”).

## 5 Summary Goals for the Next Decade

In order to test  $\Lambda$ CDM formation scenarios thoroughly, their predictions must be verified in a wide range of large stellar halos and dwarf galaxies in various stages of disruption. Cosmologically motivated simulations and star formation models make different predictions about the kinematic and chemical profiles of dSphs based on their sizes and distances; of tidal streams based on their surface brightnesses; and of diffuse stellar halos based on the total galaxy mass. Presently, the only components with observationally accessible kinematics and chemistry are nearby dSphs; high-surface brightness or very nearby tidal streams; and the MW and M31 halos. The future of these observations will depend on both new facilities and rethinking the ways in which we use existing facilities.

**Existing facilities:** In order to expand the body of spectroscopic data in dwarf galaxies using current 8–10 m telescopes, several international groups have turned to medium-resolution spectroscopy. Recent refinements to abundance measurement techniques (Shetrone et al. 2009; Kirby et al. 2009) make the most of this data. Mining data for new discoveries is, in fact, the approach that led to the recent discoveries of the tiniest known galaxies (e.g., Belokurov et al. 2007). New ways of exploiting existing data and existing facilities should not be underestimated as a major mode for new discoveries in the next ten years.

**New facilities:** An extremely large, ground-based telescope, such as **TMT** and/or **GMT**, would increase the body of kinematic data for galactic systems. It is important to measure the velocity dispersions and masses of dwarf galaxies in order to compare them to their simulated representatives. The largest telescopes today are barely able to measure velocity dispersions of the smallest dSphs around M31, and those measurements are sometimes based on fewer than 10 stars. Because only a handful of stars in each dSph are bright enough for spectroscopy, radial velocity surveys have almost certainly missed many dSphs around both the MW and M31. Furthermore, no dSph beyond the MW and M31 systems is near enough to permit measurements of stellar velocity dispersion.

**TMT** and/or **GMT** could reach more, fainter stars in known dSphs and probe larger distances to discover new ones. The next decade will witness a leap in the amount of high- and medium-resolution spectroscopic data that can be used to support or disprove the subtleties of  $\Lambda$ CDM galaxy formation. Measurements within the MW and M31 will become more refined, and galaxies beyond the Local Group will become laboratories for studying the dynamical and chemical processes that transform small galaxies into large ones. The census of dSphs around the MW will become more complete, and multi-dimensional abundance studies will shed light on the formation of M31’s stellar halo and the stellar halos of galaxies in the Sculptor and M81 Groups.

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